Attachment “2"

NATURE VOL. 305 20 OCTOBER 1983

Magnetic monopoles

Richard A. Carrigan Jr[*] & W. Peter Trower[†]

* Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
† Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA

A solitary, uncorroborated event at Stanford is the only evidence that magnetic monopoles might exist. Powerful theoretical motivation for monopoles derives from Dirac's assertion that monopoles could explain charge quantization and the 't Hooft–Polyakov demonstration that monopoles are an inevitable consequence of many gauge theories presently being used to unify the electroweak (photon–lepton) and nuclear (quark) interactions. The monopole abundance suggested by the Stanford event is in clear contradiction to bounds on their number from astronomical data. Fortunately, the already considerable and expanding arsenal of detection techniques are being fashioned to experimentally test the many open questions surrounding monopoles.

THE flush of excitement caused by Cabrera's candidate magnetic monopole event reported in 1982[1] has been reduced to a hush of activity as experimenters around the world contrive and construct detectors. One of their objectives is to corroborate or refute this solitary piece of evidence that is tantalizingly linked with the validity of the current principal theory of matter. This activity has become the focus of many scientists from formerly weakly connected disciplines: low-temperature and high-energy experimentalists, particle theorists, cosmologists and astrophysicists. Such a mixture has produced an excitement characteristic of nascent science before it is subdued into well behaved formality.

Here we review the developments in the field of magnetic monopoles before the Stanford Valentine's Day event to place this important development in context (for an earlier review see ref. 2). Next, the experimental techniques and their results are described. The important question of where monopoles, if they exist, should and should not be found is surveyed. Finally, the implications for theory of the experimental results, both actual and anticipated, are summarized; and opportunities for experiments provided by the development of new theoretical ideas are outlined (see also ref. 3).

History

Perhaps the earliest recorded discussion of magnetic monopoles is found in a letter written by Petrus Peregrinus de Maricourt in AD 1269 during a dreary siege of a rebellious Italian principality; it contains the first glimmerings of the idea of poles and lines of force[4]. The great magnetist, Gilbert, was acquainted with the Peregrinus investigations and Maxwell considered magnetic poles in his unification of electricity and magnetism but lack of experimental evidence caused them to be absent from his final formulation (C. W. F. Everitt, personal communication). In 1931, Dirac[5], fresh from the triumphant marriage of quantum mechanics and special relativity, turned to a quantum-mechanical study of a problem first addressed classically by J. J. Thomson[6]: the motion of an electric charge in the field of a magnetic monopole. Thomson had noticed the remarkable theoretical fact that the electromagnetic angular momentum in a magnetic pole–electric charge system was independent of their separation. Dirac's result is the now famous quantization condition:

$$eg = n(\hbar c/2) \tag{1}$$

where e and g are, respectively, the electric and magnetic charges and n is the principal quantum number. Stated most dramatically, Dirac demonstrated that a single magnetic pole anywhere in the Universe would explain the fact that all electric charge occurs only as discrete integral multiples of e, in essence electric charge quantization. The monopole charge is 70 times larger than the electric charge. Two consequences of this large magnetic charge are that a rapidly moving monopole should produce heavy ionization as it passes through matter and that monopoles should bind to some forms of matter. Dirac is moot on other monopole properties: size, shape, mass, parity, spin, statistics, sources, abundance, and so on.

Implicit in all the hopeful but unproductive monopole searches during the ensuing decades was the assumption that the monopole mass was comparable to other particles (for an opposing view, see ref. 7). Such monopoles could attain velocities approaching that of light and could be seen in optical detectors by their bremsstrahlung, de-excitation, Cherenkov, and transition photons. Because of their large energy loss, these monopoles would be brought to rest in matter more readily than their electrically charged counterparts. Once sedentary, monopoles would append themselves to matter from which they could be dragged with sufficiently strong, pulsed magnetic fields. Finally, although these monopoles could be found in cosmic rays, they might also be produced by an accelerator of suitably high energy.

In 1975 one event in a high altitude balloon experiment was claimed to have been produced by the passage of a monopole[8]. Its interpretation was quickly challenged on the grounds of experimental problems, incompatibilities with other work, and possibilities for a less exotic cause (see, for example, ref. 9).

The idea of looking directly for manifestations of magnetic charge using electromagnetic induction was conceived and tested in the 1960s (ref. 10). The passage of a monopole through a closed conducting ring should induce a current change intent on maintaining the ring's pre-monopole magnetic flux. Some of the original experiments were done with room temperature conducting coils. With the advent of superconducting rings in which a current change would persist indefinitely, undegraded by Joule heating characteristic of more mundane materials, these experiments became easier to carry out. The low sensitivity of current-measuring electronics in the early superconducting devices required many passages of a monopole-bearing sample to produce a palpable signal, so this technique was initially restricted to bulk matter searches[11]. However, with the development of the superconducting quantum interferometer device (SQUID), and ultra-low magnetic field shields, a dynamic monopole detector became possible[12].

Earlier in 1974, a profound theoretical insight was uncovered that would have revolutionary consequences for contemporary monopole searches. Polyakov[13] and 't Hooft[14] independently showed that monopoles appear as stable solutions of spontaneously broken Yang–Mills field equations and are required by a large class of theories (see, for example, refs 15, 16).

0028-0836/83/420673-06$01.00

Attachment "2"

Ironically, the gauge theory evoked in the successful unification of the weak, SU(2), and electromagnetic, U(1), interactions was not one of these, nor was the gauge theory responsible for the also successful quantum chromodynamics, QCD, which described the nuclear force. However, magnetic monopoles do appear in the so-called grand unification theories, GUTs, that unify strong and electroweak forces. Figure 1 schematically illustrates a GUT monopole.

In a typical GUT model there is no difference between strong, weak and electromagnetic forces at a high enough energy or temperature, say in the early Universe, because there is perfect symmetry. This energy is typically 10^{16} GeV. As the Universe expands its temperature falls and the scalar Higgs field starts to acquire a non-zero expectation value. Rapid quenching of the Higgs fields leads to topological defects[17] which are magnetic monopoles whose masses are typically $\sim 10^{16}$ GeV c^{-2}. A proton's mass is ~ 1 GeV c^{-2}.

Such large masses could only have been produced in the first instants after the creation of the Universe in the big bang. Standard cosmology and plausible GUT theory suggest that the number of monopoles is roughly equal to the number of nucleons[20,21]. On the other hand there is a serious discrepancy. As nucleons account for much of the observed matter in the Universe, there must be less than one monopole per 10^{15} protons. The presence of a galactic magnetic field implies even fewer monopoles[22]. Thus by 1981, it was argued[23] that the flux of monopoles would be no greater than 10^{-16} cm^{-2} s^{-1} sr^{-1}.

Because GUT monopoles are expected to be very massive and therefore not heavily ionizing, they would be slow, would be hard to stop, and if somehow trapped in matter, would easily be dislodged by even modest accelerations. For example, such a monopole moving at 1/100 of the speed of light could easily penetrate the earth. The most powerful electromagnet, 1 km long, would deflect the monopole less than 10^{-8} of a degree. Thus, this one idea explained why none of the experiments since Dirac's prediction would have seen a magnetic monopole. Further, it left only one detection technique free of questions—that used by the dynamic induction detector.

The candidate Stanford event of February 1982 was recorded in such an induction detector. The event possessed characteristics consistent with the passage of a particle of magnetic charge g to $\pm 5\%$ (ref. 1). The instrument which detected this monopole candidate, shown in Fig. 2, was a magnetically shielded magnetometer. The superconducting detector loop was shielded with a sophisticated superconducting shield that held ambient magnetic fields to $<10^{-7}$ G, among the lowest ever obtained. Baseline noise in the Cabrera system was typically 1% of a monopole offset signal. Although this signal is not easily attributable to any other probable cause, its possible origin in the release of some internal instrumental stress cannot be entirely ruled out. Without a second event being seen to date, this experiment has now[74] set an upper limit of 4×10^{-11} monopoles cm^{-2} s^{-1} sr^{-1} for the isotropic distribution of particles of charge $>0.06\ g$. This is 10^5 times larger than the earlier expected upper limit[23].

An induction detector has been used to examine the superconducting niobium spheres[12] on which Fairbank *et al.*[24] have reported finding fractional electrical charges. Measurements made over a decade on the niobium spheres have failed to reveal any magnetic charge. These searches were motivated by Schwinger's proposal[25] in the mid-1960s that combined both electric and magnetic charge into an object called a dyon. Experimental searches for dyons have been equivalent to those for magnetic monopoles.

Detectable properties

The presence and properties of a monopole can be deduced from their unique interactions with matter. Most techniques that are used to detect electrically charged particles have some problems for GUT monopoles so first we shall discuss an approach which can uniquely detect superheavy monopoles.

Induction: When the magnetic flux through a conducting ring is changed, a current is induced in the ring. This current is quickly extinguished by the resistance of the ring material except for a superconducting ring where the macroscopic quantum mechanical effect described by the Ginzberg–Landau formulation occurs. (Gorkov[26] demonstrated that the Ginzberg-Landau

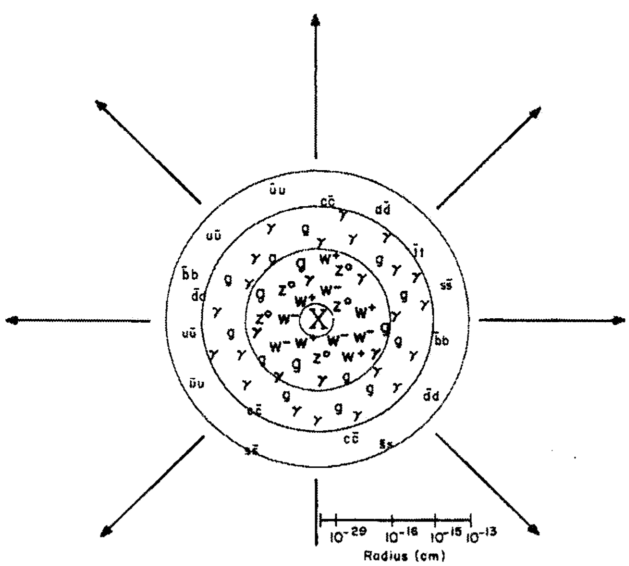

Fig. 1 The GUT monopole is structured in regions defined by the degree of unification and virtual constituents. From the inside-out there is a grand unification core where all the GUT gauge particles including X bosons are present. The electroweak unification region includes intermediate bosons (Z, W), the confinement region only has photons (γ) and gluons (g), and a fermion–antifermion condensate.

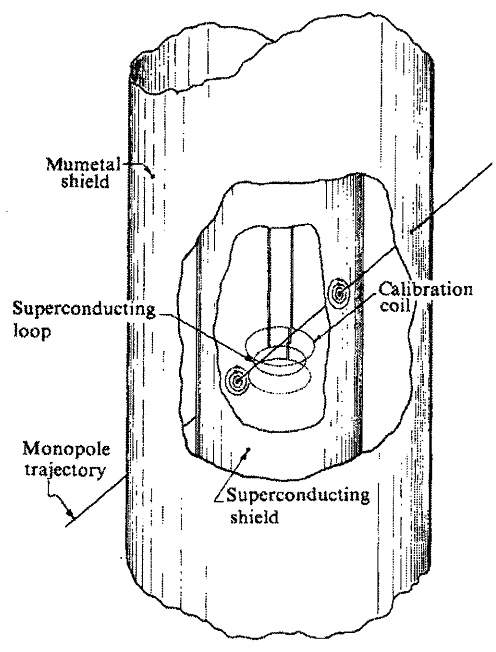

Fig. 2 Schematic diagram of the Stanford dynamic monopole detector that found the candidate monopole signal. This ultra-low field superconducting magnetometer is a four-turn 5-cm diameter niobium wire ring positioned with its axis vertical. The ring, connected to a SQUID, is mounted inside an ultra-low field shield which, in turn, is mounted inside a single mumental cylinder to provide 180 dB isolation from external magnetic field changes (taken from ref. 2).

macroscopic description of superconductivity follows from the Bardeen–Cooper–Schriffer microscopic theory.) The supercurrent density is

$$\mathbf{j}_e = \frac{he^*}{2im^*}(\psi^*\nabla\psi - \psi\nabla^*\psi) - \frac{e^{*2}}{m^*c}\psi^*\psi\mathbf{A} \tag{2}$$

where the particles involved are Cooper pairs whose mass and electric charge are twice that of the electron and $\mathbf{A}$ is the electromagnetic vector potential; ψ, the coherent many-body state of Cooper pairs, has a local pair density, $\psi^*\psi = n_s/2$, which is half the superelectron density, n_s. This equation can be solved[2] in conjunction with Maxwell's equations for a closed loop to show that the magnetic flux through the ring must be an integer number of

$$\phi_0 = (hc/2e) = 207 \text{ nG cm}^2 \tag{3}$$

the superconductivity flux quantum. For a magnetic monopole passing through a ring the flux coupling the ring has two components: the self-induced ring flux which is the supercurrent times the ring self-inductance, L, and the monopole flux coupling the ring which depends on the monopole velocity, $v(\beta = v/c$ and $\gamma = (1-\beta^2)^{-1/2})$, and the ring radius, R; c is the velocity of light. The induced ring current is

$$I(t) = (\phi_0/L)(1 + \gamma vt((\gamma vt)^2 + R^2)^{-1/2}) \tag{4}$$

The process by which a monopole pulls flux through the loop to induce a toroidal field around it is shown in Fig. 3. The characteristic time, $R/\gamma v$, is ~ 100 ns for $\beta \sim 10^{-3}$ and R of a few centimetres. For particles passing through a ring, persistent current change will only be produced by a magnetic charge. The sign of the current depends on the polarity of the magnetic charge and its direction of passage through the loop. An electric charge or magnetic dipole, as well as a magnetic charge missing the ring, will cause only small, transient current changes.

Since a changing ambient magnetic flux through the loop will also induce a current change, superconducting shields are used to freeze the ambient field in place. The shield also interacts with the loop and reduces the offset current depending on its distance from the loop. Cabrera's candidate event could have been caused by an ambient flux change through the ring although his superconducting shield is the best in the world. Other induction searches using gradiometers[27] or macromes (H. Frisch, personal communication) have opted for less sophisticated shielding in order to make larger rings. Most of these detectors, such as Cabrera's currently operating triaxial detector, incorporate multiple loops for redundancy, possible direction measurement, and increased detection area. Non-superconducting techniques have also been discussed (ref. 28 and D. Morris, personal communication). The combination of a superconducting loop, shield and SQUID appears in practice to provide the best sensitivity. Cabrera has also suggested scanning the shield with a sensitive magnetometer to detect the twin magnetic vortices left by the passage of a magnetic monopole.

Ionization: Several processes involving electromagnetic interactions of electrically charged particles result in detectable photons and concomitant energy loss for the particle. The analogue interactions for magnetic monopoles benefit from the stronger magnetic charge but suffer from the expectation that a massive GUT monopole will have a velocity much smaller than that of light.

Detailed calculations of the photon-producing processes for magnetic monopoles conclude that atomic excitation holds the most promise for monopole detection. Current energy loss estimates for GUT monopoles with β of 10^{-3} differ by several orders of magnitude[29,30,74,75]. This uncertainty has a bearing on the possibility of detecting monopoles in various media and for trapping them in astronomical bodies since their range will depend on their energy loss rate. On the other hand, ionization detectors can be made extremely large.

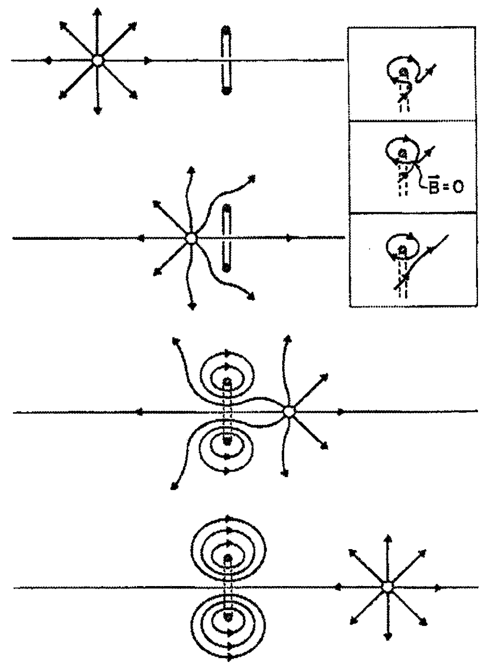

Fig. 3 Effect of a monopole passing through a current loop. The monopole effectively draws flux through the loop and leaves a residual toroidal field around it. The inset shows how the flux lines around the loop pinch off to form closed circles (taken from ref. 3).

The origin of the uncertainty in energy loss estimates lies in the fact that atomic collisions are complicated. For relativistic charged particles, these inherent complications are simplified by arbitrarily separating the interaction into two soluble classes: close collisions and distant collisions. In close collisions the energy transfers are so much larger than the electrons's binding energy that the electron is considered free and the impulse approximation is satisfactory. The energy loss is then easily calculated from simple kinematics and the scattering cross-sections. In distant collisions, the atom is considered to be excited by the perturbing electric field of the glancing particle and the dipole approximation is used.

These calculations break down when the velocity is so small that most of the collisions no longer fall into only one class; then a real model for the atom must be used to understand the dynamics. The actual calculation requires approximations to produce a result. Some years ago, Lindhard[31] worked out this theory for protons. Experiments done with protons down to β values of $\sim 10^{-3}$ are in good agreement with theory. Recently, energy loss to Zeeman splitting at low velocities has been studied from a fundamental basis[32]. Estimates of energy loss at low velocity to this mechanism in helium and hydrogen are substantially higher than ionization losses in silicon. Figure 4 summarizes the situation for the estimated energy loss.

An interesting possibility is a combination of an induction and ionization detector. If a monopole passes through such a detector and no ionization is detected within a few milliseconds of the induction event, the credibility of the ionization loss estimates and/or induction signal is called into question. Perhaps the monopole velocity is much slower than previously thought, implying an even heavier monopole. If attendant ionization is discovered, the monopole speed and direction could be determined to give the polarity of the magnetic charge.

Ionization experiments which use either plastic scintillation counters coupled to photomultiplier tubes or proportional ionization chambers typically have several detector planes spaced metres apart to signal the coordinates and time of passage of a monopole candidate event. For GUT monopoles these signals would be separated in time by microseconds. Cosmic ray events are the overwhelming source of background, so placing

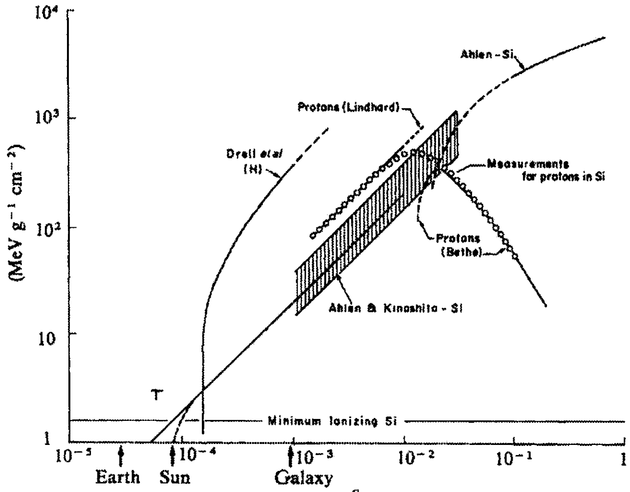

Fig. 4 Predicted energy loss rate to silicon for protons and magnetic monopoles as a function of β. The lines represent predictions while the circles are averages of proton measurements. The hydrogen calculation includes the effect of Zeeman splitting. A threshold, T, as shown for silicon, can cut off the energy loss. Reference escape velocities from the Earth, Sun and Galaxy are shown (refs 29–32).

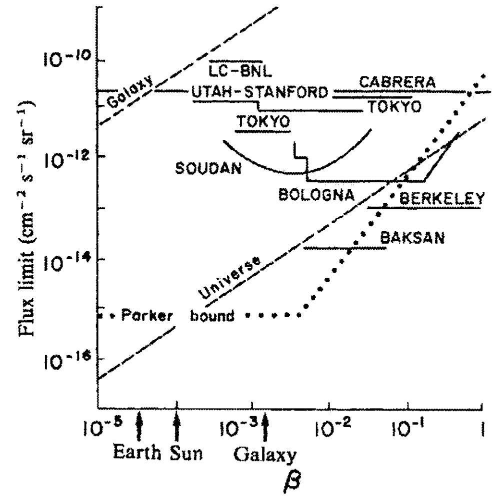

Fig. 5 Limits for cosmic-ray flux of GUT monopoles (95% confidence limits) plotted against the β of the monopole. The Stanford result corresponds to one candidate event. All other detectors relied on ionization. Also shown for monopoles whose mass is 10^6 GeV c^{-2} are the Parker galactic bound (····) and upper limits based on the expansion of the Universe for monopoles distributed uniformly and clumped in galaxies (----). (Taken from refs 42, 66–73, and B. Cabrera, personal communication.)

the detector deep underground should reduce this background. At lower velocities the energy loss is expected to be smaller, so there is a premium on making the detectors sensitive to small ionization losses.

Acoustical: Over a decade ago, Hofstader[33] suggested and demonstrated experimentally that electron beams could produce mechanical oscillations and a detectable thermoacoustic wave. Despite considerable interest in the possibilities, no particle detector has been developed using this principle due to the poor signal-to-noise ratio. Encouraged by early estimates of monopole energy loss of 2 GeV cm^{-1} (ref. 34), interest in this possibility for monopole detection has been renewed. However, calculations of the thermal fluctuation pressure suggest that this severly limits the thermoacoustic detection of monopoles for conductive media with temperatures above a few millidegrees[35]. Noise sources attendant on actual acoustic measurements are also discouragingly large. Experiments are being done to explore acoustical detection[36].

Electromagnetic: During the 1950s, five emulsion events taken in balloon flights had the unusual property that only electron–positron pairs in great number were present in a configuration which indicated a very energetic process—certainly above a few TeV—and showed no track of a causal particle[37]. These unusual events have been interpreted as photoproduction of a virtual monopole–antimonopole pair with the resulting bremsstrahlung and annihilation radiation being visible[38]. Accelerator searches have failed to discover similar events[2].

With the advent of the GUT monopole, the monopole–antimonopole system (now familiarized to monopolonium) would have been revisited[39]. Monopolonium would have some remarkable properties. At a separation of 1/10 ångstrom the lifetime of monopolonium would be as long as 10^{11} yr. At a separation of 1 Å, the velocity of the monopole in orbit is 1 cm s^{-1}, the principal quantum number is roughly 10^{12}, but the binding is still 40 keV. Monopolonium would decay by classical Larmor radiation for all but the last 10 seconds of its life. It de-excites first by emitting radio, then successively light, X rays, γ rays, quarks and gluons, intermediate bosons, and ultimately 10^{14} GeV c^{-2} X, GUT bosons. Typically some tens of millions of particles would be emitted altogether. Monopolonium radiation at a wavelength of 1 cm might produce a flux of 10^{-24} eV^{-1} cm^{-2} s^{-1} Hz^{-1}. Current observational limits are 3×10^{-16} eV^{-1} cm^{-2} s^{-1} Hz^{-1}, corresponding to 50 μJy. In general, the prospects for other monopolonium products are equally dim.

Sources and sinks of monopoles

Possible sources and sinks of GUT monopoles (with relevant problems) include: the big bang (inaccessible), monopolonium (rare), the Galaxy (extant magnetic fields), the surface of the Earth (improbable), the Sun (unlikely), the interior of the Earth (less likely than the Sun), meteorites (braking problems), accelerators (too puny), cosmic rays (rare), made by cosmic rays (still too puny), in detectors searching for proton decay terrestrially, and in neutron stars (theoretical reservations on monopole catalysis). These monopole sources and sinks are considered, moving from the nearby space-time to the big bang.

Accelerator searches: Traditionally, particle searches are most successfully carried out at accelerators. Because of the unusual properties of monopoles, it is possible to devise accelerator experiments that are background-free. No monopoles have been found in either fixed-target or colliding-beam accelerator searches[40]. Indeed, in all cases, these cross-section limits are typically the smallest measured at an accelerator. However, such searches can shed no light on the GUT monopole. Gauge theories with monopoles suggest a lower limit on the monopole mass[41], which is greater than the mass of the gauge boson associated with the theory divided by the appropriate coupling constant. For an intermediate boson mass of 80 GeV c^{-2} and the fine-structure constant, the monopole mass would be 10,000 GeV c^{-2}. (Note, however, that the standard electroweak theory does not contain a monopole.) No known accelerator technology can reach the energies of 10^{16} GeV needed to produce grand unification monopoles. Thus, accelerator monopole searches are no longer in the mainstream, but they will continue to be done as other unexpected production mechanisms might arise for monopoles that do not derive from grand unification.

Cosmic ray searches: The total cosmic ray flux at the surface of the Earth is 0.01 cm^{-2} s^{-1} sr^{-1}. The present reported Cabrera flux limit is equivalent to a hundred-millionth of this.

Astrophysical estimates of monopole flux limits[23] suggest values less than 10^{-15} cm^{-2} s^{-1} sr^{-1}. Such fluxes require detectors the size of a football field and which operate for years. The largest area-time factor reported for an ionization search is from the Baksan neutrino detector[42], which has produced a limit on the flux nearly 10^4 times lower than the current Cabrera limit. These limits are summarized in Fig. 5.

Cosmic rays can also produce elementary particles through interactions. Although cosmic ray energies range up to

10^{11} GeV, this is still too small to produce GUT monopoles. Thus, GUT monopoles found in cosmic rays would have to be primordial.

Matter searches: Monopoles could be present in matter either because they were accreted there when the matter formed or because they stopped after losing their kinetic energy. Monopoles could bind to ferromagnetic or paramagnetic material through image charges[43,44], and possibly to atomic nuclei[45]. Typically in planetary formation they would reside near the core since the force of gravity would overcome any sustaining force of matter, and gravitational forces are more significant than magnetic forces.

An obvious possibility is to search iron from the surface of the Earth. However, the expected kinetic energy of a cosmic GUT monopole is such that it could stop anywhere in the Earth's interior, so that the number of monopoles should be small and uniform through the Earth. One suggestion is to look for monopoles falling under gravity out of iron refinery operations[45], where millions of tons of surface ore are raised above the Curie point every year in the manufacture of steel. In another approach, the Earth's heat flux has been used to obtain limits on monopoles buried deep in the core[46,47].

Solar System sources: Meteors, with their smaller gravity, might provide a safe harbour for monopoles[48]. Unfortunately, a meteor-trapped monopole that hits the Earth will continue unimpeded because it carries far more momentum than the normal atoms and would shear right through matter.

The Sun has also been suggested as a source of monopoles[49]. This scenario evolved principally to explain the unexpectedly high flux suggested by the Cabrera event. In this picture the Sun contains 10^{26} monopoles and emits 10^9 monopoles per second during its lifetime. Solar flare fields expel monopoles with velocities similar to the Earth's velocity around the Sun, that is, 30 km s^{-1} (one-fifth of the typical galactic velocities), so that they form a cloud in the Earth's orbit. This model may be alone in accomodating an 11-yr sunspot cycle. However, the concentrating effect for GUT monopoles in the Sun has been calculated to be well below that needed to achieve the posited solar population[50], suggesting that a solar monopole level of this magnitude would have to be primordial.

A few observations of the Sun suggests that it has a magnetic monopole moment[51]. Taken at face value, these measurements are consistent with a net north monopole abundance of $\sim 10^{29}$ (L. W. Alvarez, personal communication). Many other more prosaic explanations have been offered for these observations[52–54].

The current view of the GUT monopole raises the possibility that when it passes through the nuclear matter, collisions may cause protons and neutrons to spontaneously decay. In other words, baryon decay, which must ordinarily be exceedingly rare, may be catalysed in the presence of a monopole. Although the possibility of baryon catalysis[18,19] has attracted much interest, there are still many questions concerning the details.

Monopole baryon catalysis offers an interesting possibility for terrestrial observations. In SU(5) grand unification, the proton lifetime has been predicted to be $\sim 10^{31}$ yr so that its detection requires large amounts of matter. On the other hand, a monopole passing through a proton decay detector could catalyse with a strong interaction cross-section, several decays. The upper limit on the monopole flux at the Earth based on the catalysis possibility is currently $<5\times10^{-15}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ in the absence of any observed events and assuming the catalysis cross-section to be ~100 mb (refs 55, 56).

Astrophysical sources: Neutron stars should be relatively good monopole collectors[57]. Once inside a star, catalysing monopoles could transform nucleons at such a rate that the resulting X-ray luminosity would exceed by many orders of magnitude the measured upper limits of neutron star X-ray luminosities. This implies a monopole flux, assuming hadronic cross-sections for catalysis, of $<5\times10^{-22}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$, much lower than any other flux limit. There are still questions about the heat transfer mechanism inside a neutron star, the catalysis rate, the micro-environment surrounding a monopole, possible recombination of monopole pairs and the superconducting interior of a neutron star which have a bearing on this argument. A non-catalysis limit of approximately the same level has been set using the millisecond pulsar (ref. 58 and J. A. Harvey, personal communication).

Monopoles are sometimes suggested as the source of the 'dark matter' which appears to be necessary to describe the dynamics of the galaxy and other large astrophysical clusters. Monopoles could supply such mass without producing much radiation.

Central to the question of galactic magnetic monopole abundance is the Parker bound[22]. Free monopoles in a magnetic field will neutralize the field since the electric currents that generate the field have to do work on the monopoles, thereby dissipating the currents. This implies that the flux limit for free monopoles is less than $10^{-16}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$, or roughly 10^5 times smaller than the Cabrera flux. This is, of course, the flux for free monopoles not bound in some way or near a monopole source.

Recently, this limit has been re-examined in detail as a function of monopole mass and velocity[59]. Even for monopoles having masses of 10^{19} GeV c^{-2}, near the Planck mass, it is difficult to achieve fluxes higher than $10^{-12}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$.

One escape from the Parker bound could be that the galactic magnetic field is due to monopoles[60,61]. If the galactic field were produced by magnetic monopoles, however, it should have a vanishing curl, which contradicts the observation. Indeed, the magnetic field configuration and magnitude generally fit the picture of a dynamo. The relatively short field oscillation time for a monopole galactic field would prevent dust grain alignment[62], a process known to exist in the Galaxy from star light polarization measurements.

Parker bound arguments can be extended to the impact of monopoles on extragalactic magnetic fields. There is evidence for intragalactic cluster fields of the order of 10^{-7} G. These low fields can be used to infer flux limits in our Galaxy a thousand times lower than the galactic Parker bound[63].

The big bang: The conundrum of monopoles in the big bang has already been mentioned[20,21]. Standard cosmology and SU(5) GUTs suggest a monopole number roughly the same as the proton number in the Universe. The estimated total protonic mass in the Universe is not far from that needed to close the Universe. If an equivalent number of monopoles with their enormously large mass is added, the Universe would have closed far too quickly. This implies that there cannot be as many monopoles as naive cosmological estimates would indicate.

Of the ways to reduce the number of monopoles, perhaps the most intriguing is the inflationary universe hypothesis[64]: in essence, the Universe expands exponentially and supercools. The actual expansion is enormous. This process erases the previous history of the Universe. After the phase transition occurs, the universe reheats and evolves along the lines of the standard big bang. With one stroke this model can severely depress monopole production[65] and explains the flatness and the horizon problems. However, the inflationary scenario has not been satisfactorily implemented in any realistic GUT model.

The future

The Cabrera event has stimulated several inductive searches, the most unambiguous way to detect a monopole. However, none of these has seen a second event so that the flux limit is now an order of magnitude lower than in 1982 and may well be an additional 100 times lower in a year or so. This is still 10,000 times the Parker limit.

The recent theoretical work on ionization of monopoles in matter has placed ionization experiments on a firmer footing down to β values of 10^{-3}. Uncertainties in ionization experiments are balanced by larger detection areas. If the many large-scale searches now underway give null results, then the largest can come close to the nominal Parker bound.

The best opportunity to answer monopole questions may lie with the grand scale of cosmology and astrophysics. Most inter-

esting would be evidence of some large-scale artefact that could be definitely linked to the existence of monopoles during some period in the evolution of the Universe.

The work was supported in part by US Department of Energy (R.A.C.) and by the NSF (PHY-80-20411) and the Jeffress Trust (W.P.T.).

1. Cabrera, B. *Phys. Rev. Lett.* **48,** 1378 (1982).
2. Cabrera, B. & Trower, W. P. *Fdn Phys.* **13,** 195 (1983).
3. Carrigan, R. A. Jr & Trower, W. P. (eds) *Magnetic Monopoles* (Plenum, New York, 1983).
4. *The Letter of Petrus Peregrinus on the Magnet, AD 1269,* translated by Brother Arnold (McGraw, New York, 1904).
5. Dirac, P. A. M. *Proc. R. Soc.* **A133,** 60 (1931).
6. Thomson, J. J. *Elements of the Mathematical Theory of Electricity and Magnetism* (Cambridge, London, 1904).
7. Carrigan, R. A. Jr *Nuovo Cim.* **38,** 638 (1965).
8. Price, P. B., Shirk, E. K., Osborne, W. Z. & Pinsky, L. S. *Phys. Rev. Lett.* **35,** 487 (1975); *Phys. Rev.* **D18,** 1382 (1982).
9. Alvarez, L. W. *Lawrence Radiat. Lab. Phys. Note* 4260 (1975).
10. Alvarez, L. W. *Lawrence Radiat. Lab. Phys. Note* 470 (1963).
11. Eberhard, P. H., Ross, R. R., Taylor, J. D., Alvarez, L. W. & Oberlack, H. *Phys. Rev.* **D11,** 3099 (1975).
12. Cabrera, B. thesis, Stanford Univ. (1975).
13. Polyakov, A. M. *JETP Lett.* **20,** 194 (1974).
14. 't Hooft, G. *Nucl. Phys.* **B79,** 276 (1974); **105,** 538 (1976).
15. Goddard, P. & Olive, D. I. *Rep. Prog. Phys.* **41,** 1360 (1978).
16. Coleman, S. HUTP-82/A032 (Harvard, 1982).
17. Kibble, T. W. B. *J. Phys.* **A9,** 1387 (1976).
18. Rubakov, V. *JEPT Lett.* **33,** 644 (1981); *Nucl. Phys.* **B203,** 311 (1982).
19. Callan, C. G. *Phys. Rev.* **D25,** 2141 (1982); *Nucl. Phys.* **B203,** 311 (1982).
20. Preskill, J. P. *Phys. Rev. Lett.* **43,** 1365 (1979).
21. Zel'dovich, Ya. B. & Khlopov, M. Y. *Phys. Lett.* **B79,** 239 (1979).
22. Parker, E. N. *Astrophys. J.* **160,** 383 (1970); *Cosmical Magnetic Fields* (Clarendon, Oxford, 1979).
23. Lazarides, G., Shafi, Q. & Walsh, T. *Phys. Lett.* **B100,** 21 (1981).
24. LaRue, G. S., Phillips, J. D. & Fairbank, W. M. *Phys. Rev. Lett.* **46,** 967 (1981).
25. Schwinger, J. *Phys. Rev.* **144,** 1087 (1966), **173,** 1536 (1968); *Science* **165,** 797 (1969).
26. Gorkov, L. P. *Soviet Phys. JETP* **9,** 1364 (1959).
27. Tsuei, C. C. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 201–217 (Plenum, New York, 1983).
28. Price, M. J. CERN-EP-82-8 (1982).
29. Ahlen, S. P. & Kinoshita, K. *Phys. Rev.* **D26,** 2347 (1982).
30. Ahlen, S. P. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 259–290 (Plenum, New York, 1983).
31. Lindhard, J. *Math.-fys. Meddr* **28,** 8 (1954).
32. Drell, S. D., Kroll, N. M., Mueller, M. T., Parke, S. J. & Ruderman, M. A. *Phys. Rev. Lett.* **50,** 644 (1983).
33. Beron, B. L. & Hofstader, R. *Phys. Rev. Lett.* **23,** 184 (1969).
34. Martem'yanov, V. P. & Khakimov, S. Kh *Soviet Phys. JETP* **35,** 20 (1972).
35. Akerlof, C. W. *Phys. Rev.* **D26,** 1116 (1982), **D27,** 1675 (1983).
36. Barish, B. C. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 219–243 (Plenum, New York, 1983).
37. Collins, G. B., Ficenec, J. R., Stevens, D. M., Trower, W. P. & Fischer, J. *Phys. Rev.* **D8,** 982 (1973).
38. Ruderman, M. A. & Zwanziger, D. *Phys. Rev. Lett.* **22,** 146 (1969).
39. Hill, C. *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 159–173 (Plenum, New York, 1983).
40. Giacomelli, G. & Musset, P. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 41–69 (Plenum, New York, 1983).
41. Bogomol'nyi, E. B. *Soviet J. nucl. Phys.* **24,** 449 (1976).
42. Alexeyev, E. N. *et al. Nuovo Cim. Lett.* **35,** 413 (1982).
43. Goto, E. *J. phys. Soc. Japan.* **13,** 1413 (1958).
44. Goto, E., Kolm, H. H. & Ford, K. W. *Phys. Rev.* **132,** 387 (1963).
45. Cline, D. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 245–258 (Plenum, New York, 1983).
46. Carrigan, R. A. *Nature* **288,** 348 (1980).
47. Turner, M. S. (EFI-82/55 Chicago, 1982).
48. Longo, M. J. *Phys. Rev.* **D25,** 2399 (1982).
49. Dimopoulos, S., Glashow, S. L., Purcell, E. M. & Wilczek, F. *Nature* **298,** 824 (1982).
50. Freese, K. & Turner, M. S. *Phys. Lett.* **B123,** 293 (1983).
51. Wilcox, J. M. *Comments Astrophys. Space Phys.* **4,** 141 (1972).
52. Sawyer, C. *Sol. Phys.* **35,** 37 (1974).
53. Stix, M. & Wiehr, E. *Sol. Phys.* **37,** 493 (1974).
54. Howard, R. *Sol. Phys.* **38,** 283 (1974).
55. Errede, S. *et al. Phys. Rev. Lett.* **51,** 245 (1983).
56. Bosetti, P. C., Gorham, P. W., Harris, F. A., Learned, J. G. & Mitsui, K. Hawaii Dumand Collaboration, 16-82 (1982).
57. Kolb, E. W., Colgate, S. A. & Harvey, J. A. *Phys. Rev. Lett.* **49,** 1373 (1982).
58. Harvey, J. A. Princeton Univ. Print-82-0868 (1982).
59. Turner, M. S., Parker, E. N. & Bogdan, T. J. *Phys. Rev.* **D26,** 1296 (1982).
60. Salpeter, E. E., Shapiro, S. L. & Wasserman, I. *Phys. Rev. Lett.* **9,** 1114 (1982).
61. Arons, J. & Blanford, R. D. *Phys. Rev. Lett.* **50,** 544 (1983).
62. Purcell, E. M. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 141–149 (Plenum, New York, 1983).
63. Rephaeli, Y. & Turner, M. S. *Phys. Lett.* **B121,** 115 (1983).
64. Guth, A. H. *Phys. Rev.* **D23,** 347 (1981); in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 81–96 (Plenum, New York, 1983).
65. Lazarides, G., Shafi, Q. & Trower, W. P. *Phys. Rev. Lett.* **49,** 1756 (1982).
66. Loh, E. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 291–305 (Plenum, New York, 1983).
67. Ullman, J. D. *Phys. Rev. Lett.* **47,** 289 (1981).
68. Groom, D. E., Loh, E., Nelson, H. H. & Ritson, D. M. *Phys. Rev. Lett.* **50,** 573 (1983).
69. Moshimo, T., Kawagoe, K. & Koshiba, M. *J. phys. Soc. Jap.* **51,** 3065 (1982).
70. Bonarelli, R. *et al. Phys. Lett.* **B112,** 100 (1982).
71. Bartelt, J. *et al. Phys. Rev. Lett.* **50,** 655 (1983).
72. Kinoshita, K. & Price, P. B. *Phys. Rev.* **D24,** 1707 (1981).
73. Price, P. B. in *Magnetic Monopoles* (eds Carrigan, R. A. Jr & Trower, W. P.) 307–324 (Plenum, New York, 1983).
74. Ahlen, S. P. *et al. Phys. Rev. Lett.* **51,** 940 (1983).
75. Groom, D. *et al. Phys. Rev. Lett.* **51,** 941 (1983).